*Submitted for publication in the.*

*Part of this paper was included in the Proceedings of the Fourth LACCEI International Latin American and Caribbean Conference for Engineering and Technology (LACCET'2006) "Educational Experiences of Embry-Riddle Students through NASA Research Collaboration" 21-23 June 2006, Mayagüez, Puerto Rico.*

# Educational Experiences of Embry-Riddle Students through NASA Research Collaboration

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## Abstract

NASA's educational programs benefit students while increasing the overall productivity of the organization. The NASA Graduate Student Research Program (GSRP) awards fellowships for graduate study leading to both masters and doctoral degrees in several technical fields, while the Cooperative Education program allows undergraduate and graduate students the chance to gain work experience in the field. The Mission Analysis Branch of the Expendable Launch Vehicles Division at NASA Kennedy Space Center has utilized these two programs with students from Embry-Riddle Aeronautical University to conduct research in modeling and developing a parameter estimation method for spacecraft fuel slosh using simple pendulum analogs. Simple pendulum models are used to understand complicated spacecraft fuel slosh behavior. A robust parameter estimation process will help to identify the parameters that will predict the response fairly accurately during the initial stages of design. NASA's Cooperative Education Program trains the next wave of new hires while allowing graduate and undergraduate college students to gain valuable "real-world" work experience. It gives NASA a no risk capability to evaluate the true performance of a prospective new hire without relying solely on a paper resume, while providing the students with a greater hiring potential upon graduation, at NASA or elsewhere. In addition, graduate students serve as mentors for undergrad students and provide a unique learning environment. Providing students with a unique opportunity to work on "real-world" aerospace problems ultimately reinforces their problem solving abilities and their communication skills (in terms of interviewing, resume writing, technical writing, presentation, and peer review) that are vital for the workforce to succeed.

## 1. Program Background

The NASA Graduate Student Researchers Program (GSRP) awards fellowships for graduate study leading to masters or doctoral degrees in the fields of science, mathematics, and engineering related to NASA research and development. The goal of NASA's GSRP is to cultivate research ties to the academic community, to help meet the continuing needs of the Nation's aeronautics and space effort by increasing the number of highly trained scientists and engineers in aeronautics and space-related disciplines, and to broaden the base of students pursuing advanced degrees in science, mathematics, and engineering. Research areas are in disciplines that lead to aeronautics and space careers. The program

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supports approximately 300 graduate students annually. Each student typically has a local Faculty Research Advisor as well as several contacts at NASA to offer advice and to aid in research. GSRP participants also have the option to utilize NASA Centers and/or university research facilities. Mentoring and practical research experiences are important aspects of the GSRP Fellowship.

The NASA Cooperative Education Programs are designed to combine academic studies with on-the-job training and experience and to give students an opportunity to work at a NASA Field Center while completing their education. Unlike an internship, which typically lasts only a summer or semester, a student in the co-op program will alternate semesters of school with work at NASA, with the intent of full time conversion upon graduation. A standard tour of duty consists of at least three semesters of work. This allows NASA to have a pipeline for qualified new hires that from experience will be good matches for their respective departments, while giving those same students the chance to preview what their job might be. Each NASA Field Center manages its own program. At NASA's Kennedy Space Center, the Cooperative Education Program is supported by many organizations throughout the center. These include Space Shuttle Processing, Spaceport Engineering and Technology, Space Station/Payload Processing, Spaceport Services, Safety/Health Independent Management, and Expendable Launch Vehicles.

Embry-Riddle is pleased to be a participant for each of these educational programs. NASA Kennedy Space Center's Expendable Launch Vehicles Division has utilized these two programs with students from Embry-Riddle Aeronautical University to conduct research in modeling and developing a parameter estimation method for spacecraft fuel slosh using simple pendulum analogs. Since the project began in August 2004, five technical conference papers with graduate and undergraduate students taking a leading role in research have been published as a result of this joint collaboration:

1. Schlee, K., Gangadharan, S.N., Ristow, J., Sudermann, J., Walker, C., and Hubert, C., Modeling and Parameter Estimation of Spacecraft Fuel Slosh Using Pendulum Analogs, AIAA/ASME/ASCE/AHS/ASC 47th Structures, Structural Dynamics and Materials (SDM) Conference, New Port, Rhode Island, May 1-4, 2006.

2. Schlee, K., Gangadharan, S.N., Ristow, J., Sudermann, J., Walker, C., and Hubert, C., Modeling and Parameter Estimation of Spacecraft Fuel Slosh, 29th Annual AAS Guidance and Control Conference, In Proceedings, Paper # AAS-06-027, American Astronautical Society, Rocky Mountain Section, Breckenridge, Colorado, February 4-8, 2006.

3. Schlee, K., Gangadharan, S.N., Ristow, J., Sudermann, J., Walker, C., and Hubert, C., Modeling and Parameter Estimation of Spacecraft Fuel Slosh Mode, In Proceedings, Winter Simulation Conference, Orlando, Florida, December 12-15, 2005

4. Schlee, K., Gangadharan, S.N., Ristow, J., Sudermann, J., Walker, C., and Hubert, C., Advanced Method to Estimate Fuel Slosh Simulation Parameters, In Proceedings, Paper # AIAA 2005-3596, AIAA/ASME/SAE/ASEE 41st Joint Propulsion Systems Conference, Tucson, Arizona, July 10-13, 2005.

5. Schlee, K., Sudermann, J., Walker, C., Gangadharan, S., and Ristow, J., Modeling Resonance in Spacecraft Fuel Slosh Using Pendulum Analogs, In Proceedings, 1st NASA/AIAA/AAS/NIA Space Exploration Conference, Orlando, Florida, January 2005.

## 2. Research Background

Spinning a spacecraft or an upper stage is a well-established method for stabilizing a space vehicle with a minimum of hardware, complexity, and expense. While spinning a deployed spacecraft over its operational lifetime has generally fallen out of style in favor of the more modern three axis stabilized active systems popular today, there still is a community of users that have to deal with spin stabilized upper stage dynamics. Many NASA and DoD payloads are launched on Boeing Delta II expendable launch vehicles with spinning solid rocket third stages. This particular version of the Delta II has been very popular for NASA interplanetary missions. Because of this, NASA's Expendable Launch Vehicle program office at Kennedy Space Center has been investigating ways to improve their understanding and ability to model spinning upper stage dynamics.

Liquid slosh in the fuel tanks of an attached spacecraft has been a long standing concern for space missions with a spinning upper stage. Loss of rotational kinetic energy through the movement of liquid propellants affects the gyroscopic stability of the combined spacecraft and upper stage. Energy loss leads to an ever increasing wobble or "nutation" which can grow to cause severe control issues (Hubert 2003). The "nutation angle" is defined as the angular displacement between the principal axis of rotation of the spacecraft and its angular momentum vector and is a measurement of the magnitude of the nutation (Wertz 1978). The amount of time it takes for the nutation angle to increase by a factor of $e^1$ is defined as the Nutation Time Constant (NTC), and is a key parameter in assessing the stability of the spinning spacecraft during the upper stage burn. The NTC can sometimes be very difficult to calculate accurately during the early stages of spacecraft design.

The current research effort proposed is directed toward modeling fuel slosh on spinning spacecraft using simple 1-DOF pendulum analogs as in Figure 1. The pendulum analog models a spherical tank. An electric motor induces the motion of the pendulum to simulate free surface slosh. Parameters describing the simple pendulum models characterize the modal frequency of the free surface sloshing motion. The one degree of freedom model will help to understand fuel sloshing and serve as a stepping stone for future more complex simulations to predict the NTC accurately with less time and effort. Various simulation parameters are estimated by matching the pendulum/rotor model response to the experimental response of full sized test tanks in NASA's Spinning Slosh Test Rig (SSTR) located at the Southwest Research Institute (SwRI) in San Antonio, Texas. The SSTR can subject a test tank to a realistic nutation motion, in which the spin rate and the nutation frequency can be varied independently, with the spin rate chosen to create a centrifugal acceleration large enough to ensure that the configuration of the bladder and liquid in the tank is nearly identical to the zero-g configuration. The propellant motion is simulated using models with various parameters (inertia, springs, dampers, etc.) and the problem reduces to a parameter estimation problem to match the experimental results obtained from the SSTR (Gangadharan et al. 1991). The data from the tests are used to derive model parameters that are then used in the slosh blocks of a MATLAB/SimMechanics-based spacecraft and upper stage simulation. Currently the identification of the model parameters is a laborious trial-and-error process in which the equations of motion for the mechanical analog are hand-derived, evaluated, and compared with the experimental results.

The current research is an effort to automate the process of slosh model parameter identification using a MATLAB/SimMechanics-based computer simulation of the experimental SSTR setup (Wood and Kennedy, 2003). Two different parameter estimation and optimization approaches are being evaluated and compared in order to arrive at a reliable and effective parameter identification process. The first approach is conducted using Newton's method for nonlinear least squares, or the MATLAB `lsqnonlin` algorithm.

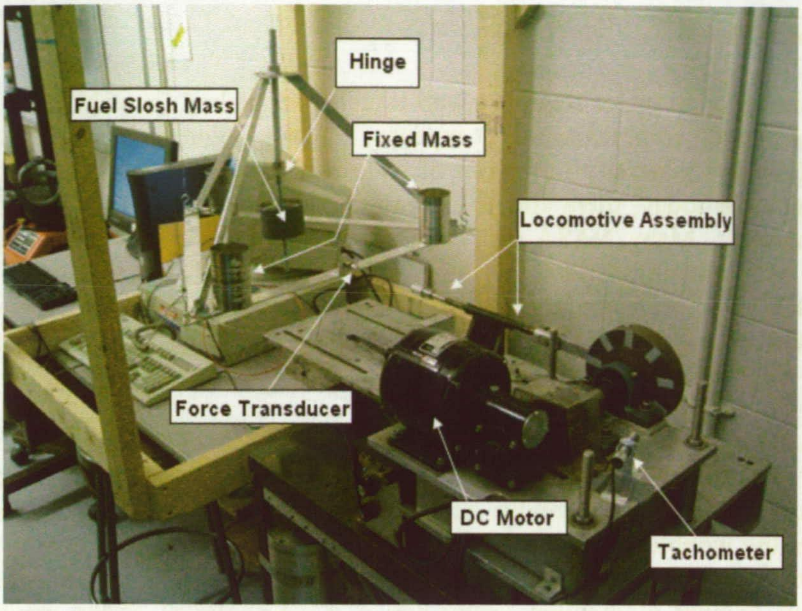


**Figure 1: A Photograph of the Pendulum Experiment at Embry-Riddle**

The second estimation method is a "black box" approach using MATLAB's Parameter Estimation Toolbox. A simple one-degree-of-freedom pendulum experiment is being used to verify each approach. By applying the estimation approach to a simple system with known characteristics, its effectiveness and accuracy can be evaluated. The same experimental setup can then be used with fluid-filled tanks to further evaluate the effectiveness of the process. This parameter estimation procedure is illustrated in Figure 2.

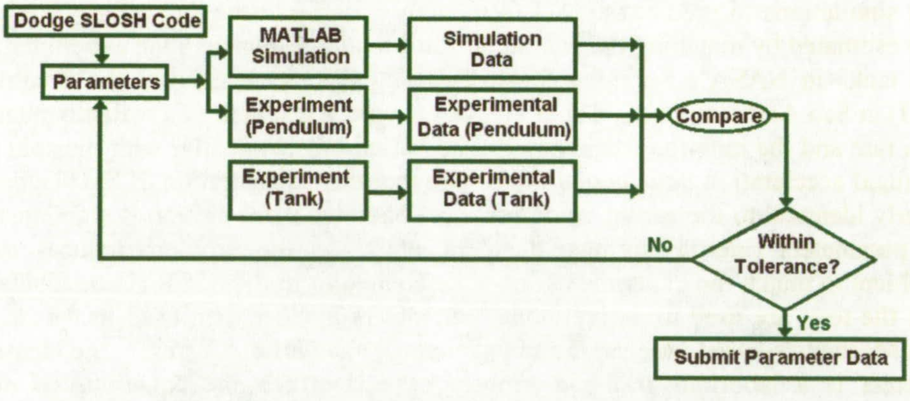


**Figure 2: Parameter Identification Process**

Ultimately, the proven process can be applied to the full sized SSTR setup to quickly and accurately determine the slosh model parameters for a particular spacecraft mission. A spherical tank undergoing free surface slosh is the simplified model for determining the pendulum parameters. Free surface slosh has a well defined resonant frequency. The only sloshing motion assumed to be taking place in this simplified model is a surface wave that in turn is simulated by the pendulum. The rest of the liquid is essentially at rest and can be treated as if it were physically frozen. The experiment and the simulation were calibrated using frozen masses. This was to verify that the model was accurately representing the experiment's way of oscillating the pendulum frame using a flywheel and locomotive arm. Examples comparing the simulation to filtered experimental data are located in Figure 3.

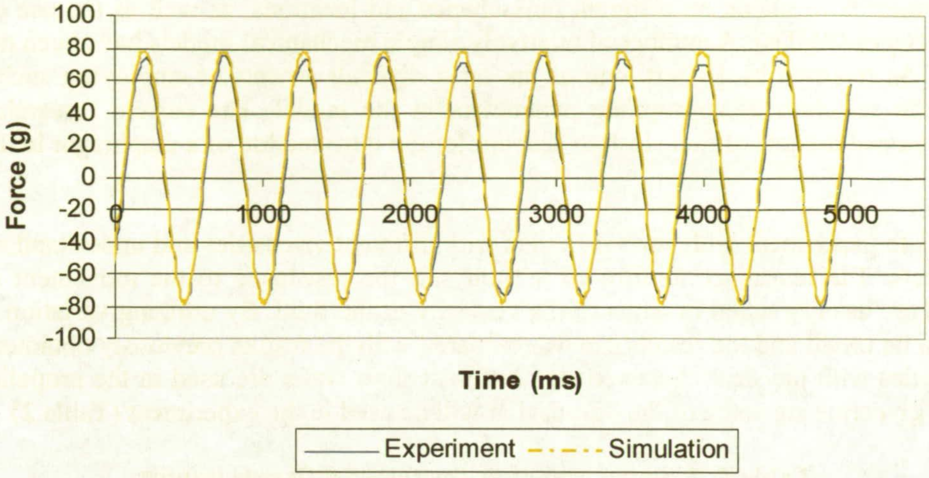


**Figure 3: Frozen Mass Testing of Experiment and Simulation for a 70% Fill Level**

This data was then used in each parameter estimation method to estimate the frozen mass. Table 1 shows a sample of frozen mass results for each method:

**Table 1: Parameter Identification Results for a 60% Frozen Fill Level**

| Actual Mass = 2.848 kg | | | | | | |
|---|---|---|---|---|---|---|
| Estimation Method | Test Frequency (Hz) | 1.660 | 1.855 | 1.953 | 2.246 | 2.441 |
| Newton's NLQ | Predicted Mass (kg) | 2.661 | 2.780 | 2.791 | 2.801 | 2.866 |
| | Mass % Difference | 6.55% | 2.40% | 1.99% | 1.65% | 0.65% |
| Parameter Estimator | Predicted Mass (kg) | 2.740 | 2.781 | 2.861 | 2.882 | 2.815 |
| | Mass % Difference | 3.81% | 2.34% | 0.47% | 1.19% | 1.16% |

The results from Table 1 illustrate the effectiveness of each estimation method. The current research is focused on increasing the number of parameters to be estimated as required for pendulum testing and analyzing the time-dependent force output caused by the pendulum. Additional parameters will be the pendulum mass, pendulum length, and pendulum joint spring/damping coefficients. Also, the pendulum model exhibits a transient region at the beginning of each test before becoming periodic as in the frozen mass testing. Methods for incorporating this into each parameter estimation process are currently underway.

***Current Research:***

After the success of the first GSRP student project experience, there is a strong motivation to continue this collaborative fuel slosh research program at Embry-Riddle Aeronautical University with other students and to advance the knowledge in this area. As with the previous project, the current research will also involve active participation of NASA and other supporting organizations.

The previous research used mechanical analogs such as pendulums and rotors to simulate sloshing mass as a common alternative to fluid modeling. The previous research was the first step to automate the process of slosh model parameter identification using a MATLAB/SimMechanics based computer simulation of the experimental SSTR setup at Southwest Research Institute. The parameter estimation and optimization approaches were evaluated and compared in order to arrive at a reliable and effective parameter identification process.

Extensive literature is available on different tank shapes and locations, as well as the use of propellant management devices (PMDs). A number of relatively simple mechanical models have been developed for these systems. As reported by Hubert, one of the most difficult aspects of employing such mechanical models is in the selection of appropriate parameters in the model. The current research will utilize previously developed models of fuel slosh to account for the introduction of a diaphragm in the spacecraft fuel tank.

The first step is to experiment with several liquids with different viscosities and understanding the lateral fuel slosh effects. The resistance to flow of a fluid and the resistance to the movement of an object through a fluid are usually stated in terms of the viscosity of the fluid. By utilizing variation of viscosity, other fluids can be tested and the results can be compared with the results previously obtained. Liquids of varying viscosities with physical characteristics different from water are used in the propellant tank and tested. Oil and glycerine are some of the liquids that will be used in the experiment (Table 2).

**Table 2. Comparison of viscosities of different liquids**

| Liquid | Viscosity (Poise) |
|---|---|
| Water | 0.01 |
| Oil (heavy) | 6.6 |
| Oil (light) | 1.1 |
| Glycerine | 14.9 |

According to Ibrahim, for higher viscosities the resonance frequency is slightly higher that the predicted value for an ideal liquid. The results of the data obtained from the new liquids introduced to the experiment will evaluate the effectiveness of the fuel slosh modeled previously.

Flexible diaphragms and positive expulsion devices that provide an impermeable barrier between the liquid and the gas in a tank are employed in tanks when there is a need to transfer liquid in a low gravity environment or when a high flow rate is desired without pumps. The flexible diaphragm is attached to the periphery of the tank wall. Because of the geometric constraints, a flexible diaphragm is most commonly used in spherical propellant tanks. Diaphragms provide a substantial level of slosh damping as a result of the combination of viscoelastic flexing of the diaphragm and the increased viscous effects at the liquid-diaphragm interface. A diaphragm also increases the slosh natural frequency because of the constraints imposed on the free surface shape. The effective mass of liquid participating in the sloshing is slightly smaller than for a tank of the same shape and fill level without a diaphragm (Dodge and Kana ).

Figure 4 illustrates the introduction of a diaphragm to the experimental set-up. According to Quadrelli, the nutation characteristics of the system also depend on the dissipation induced by the liquid viscosity, as well as on the presence and damping characteristics of the PMD. An example of the diaphragm application in the space program is the semi-rigid elastomeric diaphragm that is being used in *Deep Space One*. The diaphragm material that will be used in the experiment will be an elastomeric material.

The ultimate goal of this research collaboration is to automate the parameter identification process. This will save time and thus allow earlier identification of potential vehicle performance problems. This in turn, can reduce the cost and avoid delays associated with design modifications. Applications of an automated process to find the NTC will benefit all space exploration missions involving spinning spacecraft. Using a combination of test derived fuel slosh parameters and computer simulations of the spacecraft dynamics, an improvement in the current ability to make predictions of NTC can be achieved.

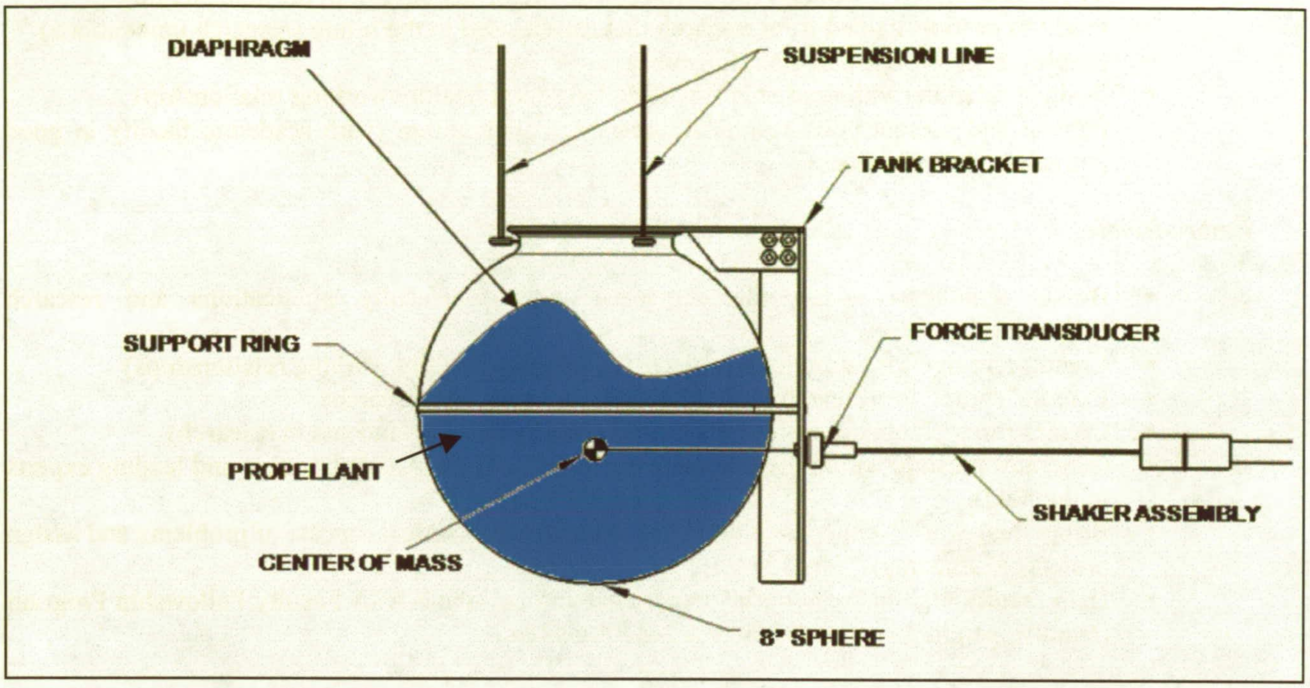


**Figure 4:** Schematic diagram of experimental set-up with the diaphragm

## 3. Joint Benefits of Research Collaboration

The above abstract represents a small sample of the work that has been accomplished as a result of the GSRP and Cooperative Education program and parallels similar collaborating efforts between universities and industry (Hendley, 1997). Benefits are numerous for both Embry-Riddle and NASA. The benefits gained by students, NASA, and Embry-Riddle are listed below:

***Students***

- Research experience (practical work experience)
- Communication skills (presentation, technical writing, resume writing, and interviewing)
- Reference letters (for jobs, internships, co-ops, and part-time opportunities)
- Contacts for jobs (networking in the "real-world")
- Exposure to work environment and responsibility (lead role in research, meeting deadlines, and working under pressure)
- Active participation in conferences (presentation and answering questions)
- Bridging the gap between government agencies and academia (by understanding the differences)
- Exposure to "real-world" project peer review process (answering technical questions and suggesting future work)
- First-hand look and experience of the Aerospace field (practical projects and actual prototype testing)

***NASA***

- Fresh, creative minds with new outlook to solve their problems (through students and faculty)
- Economical resource (student involvement and university resources/labs)
- Venue to complete side tasks (projects that are important but not in the mainstream)
- Products or tools gained from research that can be used in the future (research innovations)
- Employment (co-ops/part-time/full-time)
- Positive relations with academia (favoring long-term healthy working relationship)
- Publish and present good technical papers in collaboration (with academic faculty in good journals and conferences)

*Embry-Riddle*

- Builds reputation within the aerospace industry (faculty publications and research collaborations)
- Creates a bridge for future joint projects (developing healthy working relationships)
- External source for research ideas (practical problems for research)
- Creates research opportunities for students (faculty involve students in research)
- Generates prestige within the academic community (NASA collaboration and leading experts in the field)
- Bring "real-world" experience into classroom (teach practical aspects of problems and assign projects to students)
- Help faculty to gain "real-world" experience through the NASA Faculty Fellowship Program (faculty spending summer months at NASA centers)

## 4. Supporting Organizations

The research collaboration for this project has been supported by a several organizations in industry along with Embry-Riddle and NASA. These include The MathWorks, Southwest Research Institute (SwRI), and Hubert Astronautics. All of these organizations have helped in this research signifying a true collaborative effort between industry, government, and academia. A block diagram illustrating the involvement of each organization is shown in Figure 5.

## 5. Conclusions

The role that Embry-Riddle has played in each NASA-sponsored educational program has had a tremendous positive reaction from all organizations involved. Future collaboration between each organization is continuing at Embry-Riddle with new fuel slosh research goals already in the works. Future research opportunities on other projects are now a possibility due to the successful relationship that this research collaboration project has forged.

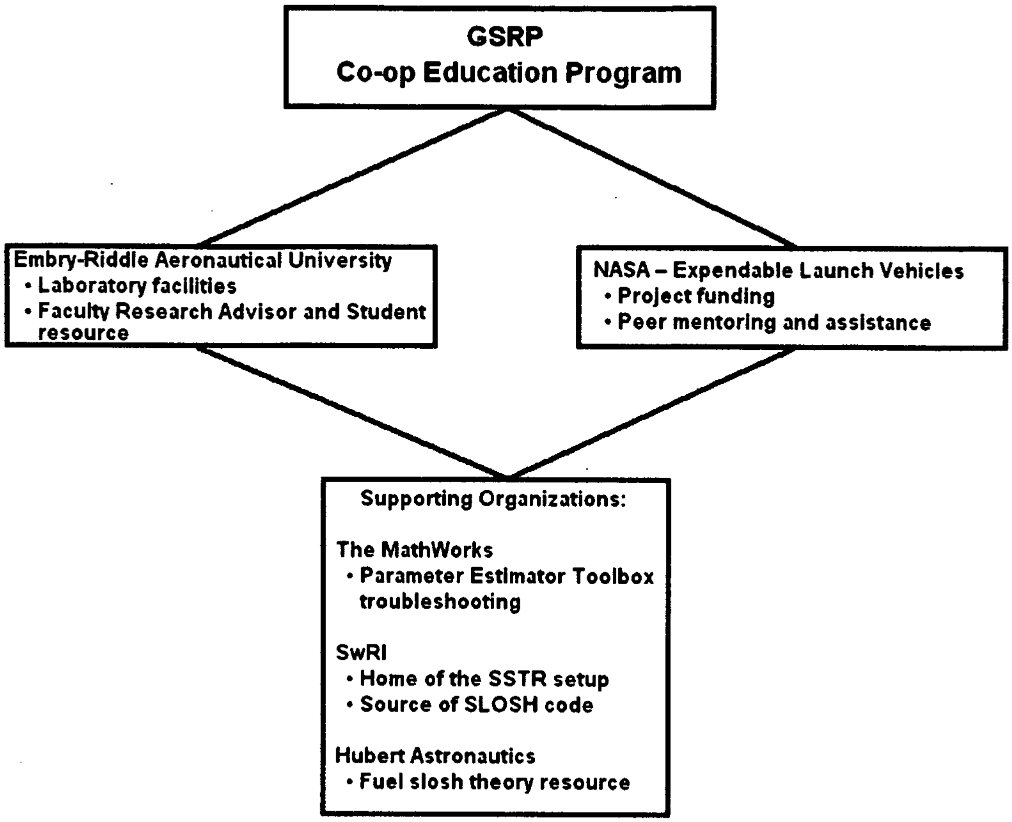


**Figure 5: Block Diagram of the Organizational Structure of NASA/Embry-Riddle Fuel Slosh Program**

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